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Climate-change potential effects on the hydrological regime of freshwater springs in the Italian Northern Apennines

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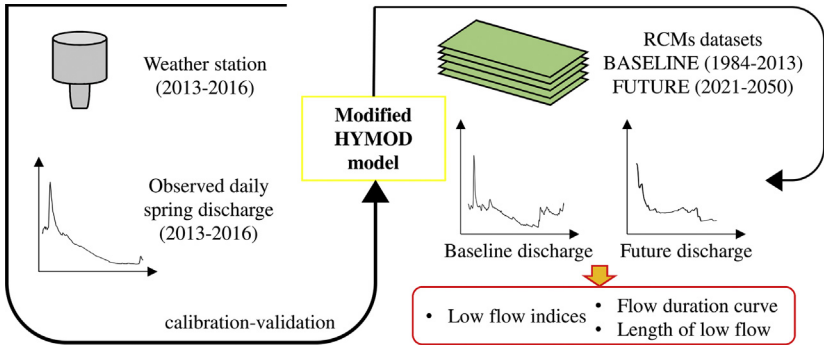
HIGHLIGHTS

- a lumped rainfall-runoff model was optimised to simulate daily discharge of a group of springs from Northern Italy
- future climate forecasts will induce a change of seasonal discharges, which will be more marked in summer and autumn seasons
- low flows will be affected while years with long periods of consecutive days with low flow are expected to be more frequent

GRAPHICAL ABSTRACT



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ABSTRACT

In large areas of the Italian Northern Apennines, hundreds of low-yield springs provide water for drinking and industrial purposes, with short groundwater flow paths being formed within fractured sedimentary rock units. This hydrogeological setting results in spring water discharges that closely follow meteoric water recharge patterns, leading to low-flow periods concentrated in the summer/early autumn. Therefore, the springs' outflow can be very sensitive to a shortage in water recharge, as it was the case in 2003 and 2017, when a prolonged period of drought caused severe water management issues. This work analyses how a group of such springs responds to climate change. In particular, we first validated a hydrological rainfall-runoff model on the basis of daily discharge data collected between 2013 and 2016. Then, outflows were simulated for baseline (1984–2013) and future periods (2021–2050) using weather data provided by five RCM-GCM combinations. Finally, we performed statistical analyses aiming to examine the intra-annual variability in discharge rates, low-flow indices, flow-duration curves and the length of low-flows. Results show no evidence of change in mean annual discharges, but future climate estimates suggest a slight change to seasonal discharges in the future, with a marked increase of discharge during winter and spring, and a decrease in summer and autumn. Q(95) and 7Q10 low-flow indices (i.e. the daily discharge exceeded 95% of the time and the minimum weekly discharge associated with a 10-year recurrence interval, respectively) are significantly affected by the climate change (−21.8% and −25.0%, respectively), while droughts are expected to be more frequent: the number of years with a consecutive low-flow between 51 and 100 days to increase by a third, and between 101 and 150 to duplicate.

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1. Introduction

As a consequence of climate change, the regional hydrological cycles in many areas across the world have already or will in future be altered (Huntington, 2006; IPCC, 2007). In particular, several studies have underlined the effect of climate change on the available surface water and groundwater, both in terms of present observations and future forecasts (Arnell, 1998; Jarsjö et al., 2012; Taylor et al., 2013; Levison et al., 2014). This is more evident when the aquifer's resilience (sensu Holling, 1973: the ability to absorb change and disturbance and still maintain the same relationships between state variables) is so low that it fails to mitigate the changes to rainfall amounts and patterns (Dragoni and Sukhija, 2008). Aquifers with both a small-sized recharge area and low yield are expected to face the most critical conditions, from both a qualitative and a quantitative standpoint (Kløve et al., 2014).

In the Italian Northern Apennines, future climate scenarios contemplate an increase in mean temperature of around 1.5–2.0 °C in all seasons until 2050 (Tomozeiu et al., 2014). This could lead to changes in evapotranspiration fluxes and, as already pointed out for this area (Hiscock et al., 2011; Dubrovský et al., 2014), to a decrease in aquifers recharge. Furthermore, the mean annual rainfall is expected to slightly decrease (Giorgi and Lionello, 2008; Lionello et al., 2014), and changes in rainfall distribution during the year are forecasted, together with an intensification of rainfall events (Coppola and Giorgi, 2010). Both conditions will act in an area where there are hundreds of springs with a discharge of less than a few l/s during the low-flow period (sensu WMO, 1974: flow of water during prolonged dry weather), renewing the groundwater stored within the aquifer almost completely every hydrological year (Corsini et al., 2009). The cause of this depends on the presence of relatively superficial and short groundwater circuits where low-yield unconfined aquifers develop (Gargini et al., 2014; Cervi et al., 2015). The rainfall pattern and springs' discharge peaks are seen to be closely inter-related. These hydrogeological characteristics complicate the water resources management in the area, especially during the dry season, i.e. when the consumption of drinking water increases because of seasonal tourism.

Several authors have dealt with the relationships between climate change and the groundwater recharge-discharge processes in many mountainous areas across Italy (Alps: Gattinoni and Francani, 2010; Apennines: Cambi and Dragoni, 2000; Fiorillo et al., 2007; Fiorillo and Guadagno, 2010; Fiorillo and Guadagno, 2012; Di Matteo et al., 2013; Fiorillo, 2014; Dragoni et al., 2015; Fiorillo et al., 2015). Concerning the Apennines, it is worth noting that the above studies focus on the changes to groundwater quantities in springs located in the central and southern Apennines, where discharges are fed by aquifers composed of large carbonate-rock units, with annual yields in the order of $10 \div 80$ Mm^3. The situation is completely different in the Northern Apennines.

This work looks at the effects of climate change on groundwater resources in the latter area, a topic that is yet to be investigated, by applying a hydrological model that simulates a representative group of springs (Mulino delle Vene springs; Cervi et al., 2014). The model was calibrated and validated on spring discharges collected between 2013 and 2016.

Daily climate data from each of five Regional Climate Models (RCMs), specified later, were used as input to the validated hydrological model to simulate spring discharges up to year 2050. Since fresh water springs are the main source of water supply, the results are discussed in terms of water management, focusing in particular on intra-annual variability and low-flow indices, flow duration curves and the duration of low-flow periods. Moreover, further considerations are also provided about the possible influence of the estimated future spring discharges on surface water and groundwater in terms of the Northern Apennines overall.

2. Study area

The Mulino delle Vene springs are located in the Northern Apennines, in Italy, at an elevation of 420 m a.s.l. They consist of several springs discharging from a 50-metre-long rock face into the river Tresinaro, a few metres downstream (Fig. 1). The springs are fed from a rock-slab aquifer composed of intensively fractured arenites, and the relative recharge area has been estimated to be about 5.5 km^2 (Cervi et al., 2014; Fig. 1). The recharge area of the aquifer (mean altitude of 620 m a.s.l.) extends across a gentle slope in a non-urbanized area.

Rainfall data collected between 2004 and 2014 at the weather station of Carpineti (580 m.a.s.l.) show a cumulative annual rainfall depth ranging between 489 mm and 1274 mm (mean value of 887 mm) and two main wet seasons in March–April and October–November. Cumulative annual snowmelt varied between 35 mm and 76 mm of equivalent water, concentrated between December and February (see http://www.arpa.emr.it/sim/?telerilevamento/innevamento); the snowpack, when present, covers the ground continuously for less than 30 days per year (starting in January–February). During the same period (between 2004 and 2014), using the Thornthwaite and Mather (1957) approach, the mean annual effective rainfall (i.e. the part of precipitation that remains at ground surface after evaporation and transpiration processes and is thus available for subsequent infiltration and runoff) has been assessed in about 476 mm (min 220 mm and max 637 mm), mainly occurring between November and March.

With reference to the recharge area, the lack of runoff in the streambeds during the whole year suggests that almost all meteoric water can be considered as recharging the aquifer (Cervi et al., 2014). In 1995, a weir was constructed on each of two springs located close to each other. However, no total discharge data were available until 2012, when a study was carried out to assess the overall groundwater discharge released and a rating-curve was obtained linking the combined discharge with the water level in one weir (Cervi et al., 2014). An electric transducer was subsequently placed at one weir to assess the discharge from all the springs (on 11th March 2013). The data acquisition time-step was set at 1 h and the monitoring is still ongoing. By focusing on the available daily data until September 2013, Cervi et al. (2014) were able to show that the Mulino delle Vene springs have one of the highest discharge rates among all springs in the Northern Apennines.

Between 11th March 2013 and 31st May 2016 discharges range between a maximum value of 462.9 l/s (occurred on April 5th, 2013) and a minimum about 28.4 l/s (occurred on November 14th, 2013), showing an overall mean value equal to 96.8 l/s (see Fig. 2) and main peaks between March and April. The daily discharge values follow closely the rainfall and snowmelt patterns, with a time-lag in the order of a few days during the wet seasons.

3. Methodology

The procedure consisted of monitoring the springs' discharge and processing of hydrological and weather data in order to optimise the well-known Hymod model (Boyle, 2001), a conceptual rainfall-runoff model belonging to the class of probability distributed models (see e.g. Moore, 2007). The model was firstly calibrated over the period 11th March 2013–4th November 2014 and successively validated over the period 5th November 2014–31th May 2016.

The datasets provided through five RCMs were used to assess the daily weather data in the future (2021–2050), while the corresponding data for the baseline period (1984–2013) were collected from a weather station. These data were then used as input to the hydrological model to assess possible future variations of the streamflow regime of spring daily discharges and potential changes in terms of intra-annual variability, low-flow indices, flow-duration curve and the length of low-flows.

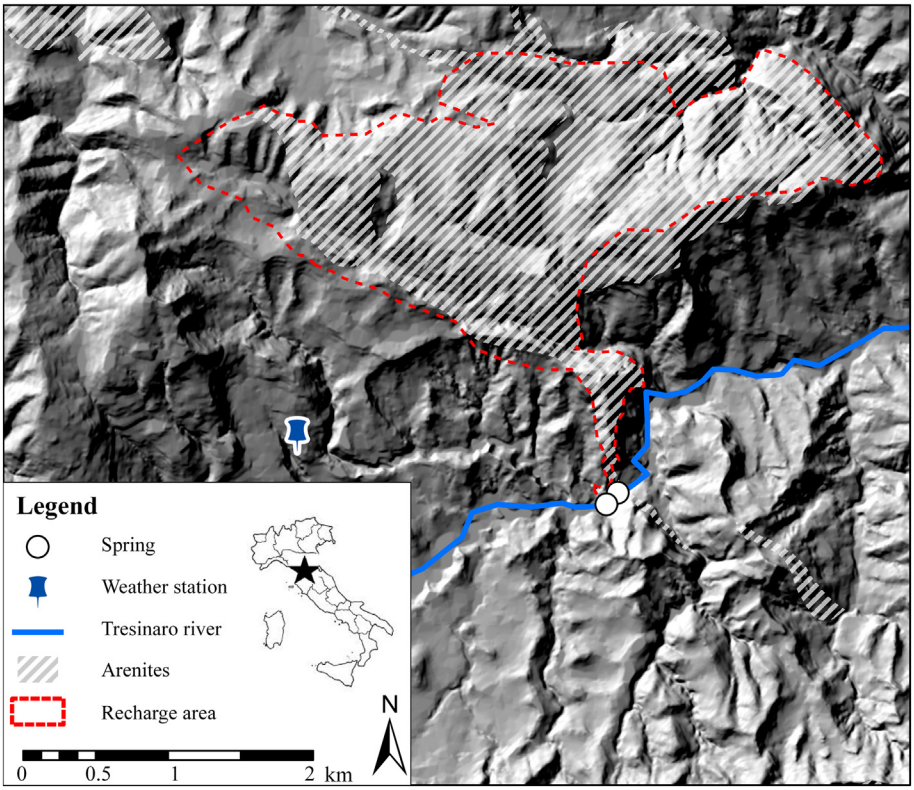

Fig. 1. Study area. The recharge area corresponds to a part of the arenite slab. The Mulino delle Vene springs originate at the southern termination of the recharge area, near the Tresinaro River.

3.1. Hydrological modelling

The modelling of fractured aquifers is still a difficult task; this is mainly due to their heterogeneous hydrogeological properties and because there is very little continuous monitoring data on piezometric levels (Angelini and Dragoni, 1997; Voeckler and Allen, 2012).

Lumped hydrological models (i.e. models in which the hydrological processes are conceptualized by a set of equations transferring rainfall input into an outflow) have been successfully used for simulating not-porous hydrogeological systems, such as karst aquifers (Barrett and Charbeneau, 1997; Martínez-Santos and Andreu, 2010).

The Hydrological MODel (HyMOD) belongs to the aforementioned conceptual lumped rainfall-runoff models. It was proposed by Boyle (2001) starting from the Probability Distributed Moisture (PDM) introduced by Moore and Clarke (1981); this specific approach implies that the spatial variability of some parameters such as soil structure and water storage capacity, is represented through probability distribution functions. HyMOD was developed to simulate the outflow from catchments (Wagener et al., 2001; Vrugt et al., 2003; Montanari, 2005; Bastola et al., 2011; Soundharajan et al., 2013) and consists of a simple rainfall-excess model connected with two series of linear reservoirs in parallel. The rainfall-excess model assumes that the soil moisture in the catchment varies in time and in space. In particular, the spatial variability of soil moisture capacity C is described by a Pareto distribution function:

$$F_C(c) = 1 - \left(1 - \frac{c}{C_{max}}\right)^{\beta_k}, 0 \le c \le C_{max} \quad (1)$$

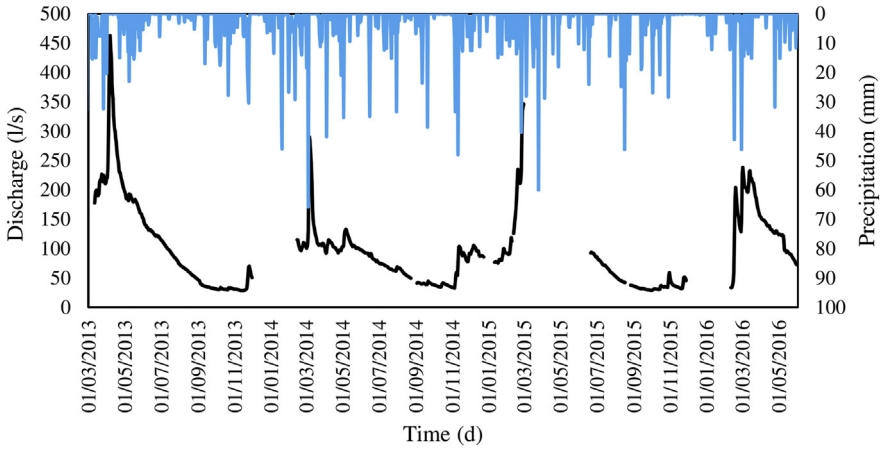

Fig. 2. Daily discharge (in l/s) from 11th March 2013 to 31st May 2016 measured at the Mulino delle Vene springs together with precipitation (in mm). In the periods between 1st December 2013 and 12th February 2014, 1st March 2015 and 19th June 2015, 28th November 2015 and 9th February 2016 the electric transducer installed in the springs was out of work.

where $F_C(c)$ is the cumulative probability of a given water storage capacity c [L]; β_k [−] is the degree of spatial variability of the soil moisture capacity within the catchment; C_{max} [L] is the maximum storage capacity in the catchment.

The rainfall-excess model assesses, for each time step, the actual evapotranspiration (AET, function of potential evapotranspiration ETP and of the soil water capacity) and the effective rainfall (ER = ER1 + ER2) which are used as input to the model module performing the flow routing to the catchment outlet.

The original routing module consists of two lines, the first simulating the quick response (runoff, quick line) and the second simulating the slow one (sub-surface flows, slow line). The input to this module is divided between the two lines by a weight α [−], varying between 0 and 1, meaning that αER is the input to the quick line, while (1-α)ER is the input to the slow line.

The quick line consists of a Nash cascade of three linear reservoirs with residence time K_q [T]. The slow line consists of a single reservoir with residence time K_s [T]. The total discharge Q(t) from the catchment is equal to the sum at time t of the discharges from each line.

As anticipated in Section 2 and with reference to the Mulino delle Vene springs, it must be highlighted that in the recharge area the creeks show almost no discharge during the year, meaning that almost all the effective rainfall can infiltrate through the soil with no runoff processes.

Moreover, during the wet seasons Mulino delle Vene springs' discharges are characterized by a non-negligible time-lag with respect to rainfall events, that is in the order of some days. This allowed us to use a simplified version of HyMOD that neglects the quick line (α is set equal to 0) and considers water from the water-excess model going directly to the slow line (Fig. 3). In this way, the parameters of the simplified Hymod are reduced to three (instead of five), i.e. the water-excess model (C_{max}, β_k) and the residence time of the slow line (K_s).

A similar scheme was adopted by Tomesani et al. (2016) to simulate the groundwater flow feeding the Lake of Monate in Northern Italy.

Once the hydrological model was set-up, daily discharges were reproduced over the period monitored, 2013–2016, using the daily precipitation (P) and the daily potential evapotranspiration (ETP) as input and considering the extension of the recharge area (5.5 km^2, as reported by Cervi et al., 2014).

It is worth noting that ETP was estimated through the Hargreaves equation (Hargreaves and Samani, 1985). As suggested by Smith et al. (1991) and Allen et al. (1998), the ETP had previously been calibrated through the Penman-Monteith equation for the period 2009–2016. Datasets for the period 2009–2016 (daily precipitation, mean minimum and maximum temperature, minimum and maximum air humidity and wind speed) related back to the Carpineti weather station (Fig. 1).

HyMOD was calibrated through the Relative Efficiency (E_{rel}) and the Inverse flow efficiency (NSE_i) using the observed daily discharge values from 11th March 2013 to 4th November 2014, then it was validated on the remaining dataset, from 5th November to 31st May 2016. E_{rel} and NSE_i are modifications of the Nash and Sutcliffe coefficient (Nash and Sutcliffe, 1970) that assign more relevance to low-flows in assessing model performance; they are also recommended for low-flow simulation by Krause et al. (2005) and Pushpalatha et al. (2012). The two functions are defined as follows:

$$E_{rel} = 1 - \frac{\sum_{i=1}^{n}\left(\frac{Q_i^{obs} - Q_i^{sim}}{Q_i^{obs}}\right)^2}{\sum_{i=1}^{n}\left(\frac{Q_i^{obs} - Q_{mean}^{obs}}{Q_{mean}^{obs}}\right)^2} \quad (2)$$

$$NSE_i = 1 - \frac{\sum_{i=1}^{n}\left(\frac{1}{Q_i^{obs}} - \frac{1}{Q_i^{sim}}\right)^2}{\sum_{i=1}^{n}\left(\frac{1}{Q_i^{obs}} - \frac{1}{Q_{mean}^{obs}}\right)^2} \quad (3)$$

where Q_i^{obs} is the i-th discharge observation, Q_i^{sim} is the i-th discharge simulation, Q_{mean}^{obs} is the mean observed discharge and n is the total number of observations. The coefficients range between −∞ and 1 with higher values indicating less error variance.

3.2. Baseline and future scenarios

The baseline period (1984–2013) is composed of the observed weather data acquired from the Carpineti rain gauge (Fig. 1). The datasets for the future period (2021–2050) were constructed by processing the forecasted climate datasets provided by five Regional Climate Models (RCMs), obtained through the ENSEMBLE project (Hewitt, 2004). In reality, whereas the series of observed data are commonly considered as the baseline for hydrogeological simulations, using non-processed RCM outputs could bring about unrealistic estimates (Holman et al., 2009). This is because the climate model records show statistical distributions that are significantly different from those of the observed data. It is, therefore, necessary to subject the raw RCM records to model output statistics post-processing. The RCMs, specifically HC HadCM3Q0, ETHZ HadCM3Q0, KNMI ECHAM5-r3; MPI ECHAM5-r3 and SMHI ECHAM5-r3, cover the period 1961–2050 and have a spatial resolution of 25 km. The projections are based on a A1B SRES IPCC scenario (IPCC, 2007), which describes a consistent economic growth coupled with an increase in population until the mid-21st century, in combination with the rapid introduction of more efficient technologies and balanced energy sources.

First at all, model records have been projected onto the Carpineti station position with a weighted average of the model grid-points closest to the station itself, based on a Gaussian weighting function that decreases to 0.5 at the distance of 12.5 km.

Then, the future daily datasets were downscaled through the Cumulative Distribution Function technique, CDF-t (Michelangeli et al., 2009; the R package used in this study is available for free on the CRAN website: http://cran.r-project.org/web/packages/CDFt/index.html), which belongs to the group of Quantile-matching methods. Differently from the delta-change approach commonly used in hydrological studies, this procedure provides more reliable estimates of future variability and the occurrence of extreme events, making it possible to carry out a proper investigation concerning the intra-annual and inter-annual discharges, as well as low/high flow features.

The approach is based on the assumption that, by using a specific transformation assessed comparing the observed and the RCMs datasets, it is possible to "translate" the CDF of a model variable (in our case daily minimum, maximum temperature and rainfall, i.e. the parameters required for the Hargreaves equation) into the CDF representing the local-scale climate variable, i.e. the given weather station (Déqué, 2007; Michelangeli et al., 2009; Stoll et al., 2011).

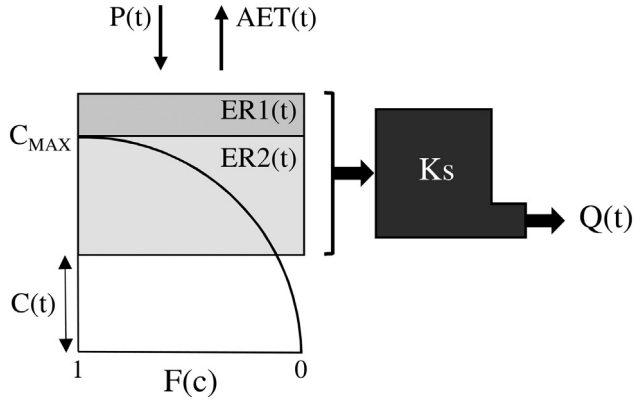

Fig. 3. Hydrological model (modified Hymod) of the fractured aquifer feeding the Mulino delle Vene springs.

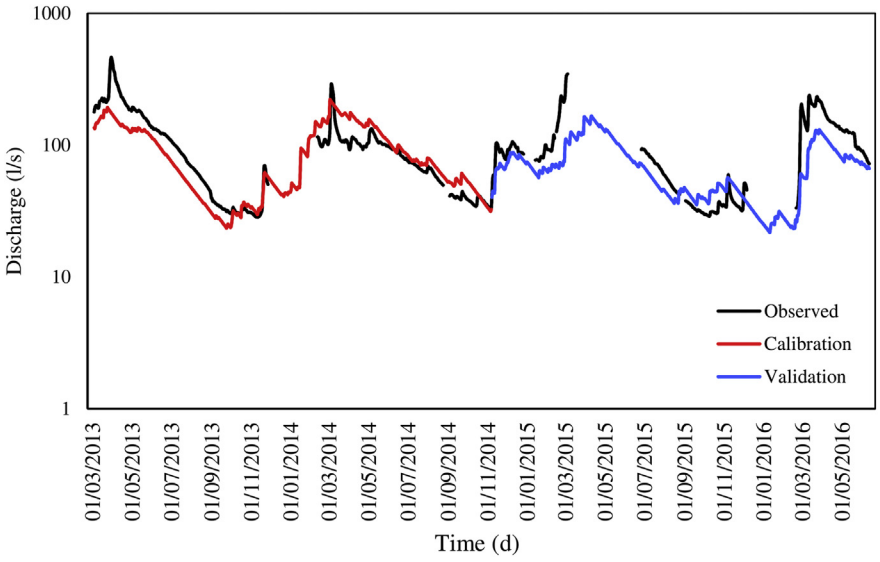

Fig. 4. Simulated vs. observed discharge (in l/s) for the period 2013–2016. Simulated discharge is distinguished for calibration (red line) and validation (blue line) periods.

With reference to rainfall, it must be highlighted that, before applying this procedure, the model series must reflect the same frequency rate as that of the corresponding observed baseline record (1984–2013). This involved pre-filtering the data by estimating, for each month, the observed and the modelled mean frequency of wet days and then applying the observed frequency to the whole RCMs series by setting a value as the threshold that is below the daily rainfall.

Afterwards, in the model's datasets, the daily rainfalls and the minimum and maximum temperatures have been processed using the Hargreaves equation (Hargreaves and Samani, 1985) to obtain the daily potential evapotranspiration (ETP) which is required as the input for the hydrological model.

In order to assess the statistical significance of the changes to the meteorological variables and the discharges, it was necessary to apply Student's *t*-test to the baseline and the future periods. A *P*-value below 0.05 was considered as the upper threshold of significance.

Finally, the downscaled RCMs datasets for the future period (2021–2050) were processed and reported as average values together with a standard deviation in order to reduce the uncertainties connected to the RCM selection (Fowler et al., 2007).

3.3. Flow-duration curves, low-flow indices and low-flow length

We focus on several indices of low-flow regime, namely: flow-duration curves (FDCs); Q(95); 7Q10; and duration of low-flow period, which have been widely used in water resource management processes (Smakhtin, 2001; Pyrce, 2004). They were calculated directly from multi-annual series of daily discharge data collected through the gauges (Tallaksen and van Lanen, 2004) and on future estimates (Wilby et al., 1994; Bekele and Knapp, 2010; Gunawardhana and Kazama, 2012). In detail, FDCs illustrate the percentage of time, or probability, that a spring's discharge is equal or greater than a particular value over a specified period of time. Long-term average annual FDCs, obtained from 30-year time series (FREND, 1989; baseline and future periods), were used in this study.

According to these definitions, Q(95) (l/s) coincides with the 95th percentile of the FDC of interest and is calculated, similarly to the FDCs curves, by processing the baseline and future 30-year time series.

The 7-day 10-year low-flow index (7Q10; l/s) belongs to the group of low-flow frequency curves (LFFCs; Smakhtin, 2001) and, unlike the FDCs, shows the average interval in years (called 'recurrence interval') when the daily discharge falls continuously below a certain value. Among the several average intervals proposed in literature, 7Q10 is one of the most commonly used indices and is usually estimated through a Log-Pearson type III distribution function (Smakhtin, 2001). In this work, the baseline (period 1984–2013) and future (period 2021–2050) low-flow series were used to calculate this statistical distribution.

Finally, the continuous low-flow distributions were analyzed using the dry-spell approach (Institute of Hydrology, 1980), where by spell we mean the number of days when daily discharges remain below a defined threshold. This threshold can be set by referring to the FDCs (Beran and Gustard, 1977) and the 80th percentile (i.e. Q(80)) is a common threshold value when considering rivers or springs with perennial discharges (Smakhtin, 2001). Therefore, the FDCs obtained from the baseline and future periods also provided us with the Q(80) values that we subsequently used as thresholds.

Results are presented in the form of a histogram showing the number of years where the spell is below the given threshold (Q(80)). The mean number of consecutive days when the discharge is below the threshold is also given for the baseline and future periods.

4. Results

4.1. Hydrological modelling: calibration and validation

HyMOD was calibrated for the period between the 11th of March 2013 and the 4th of November 2014 by comparing observed and simulated discharges of the Mulino delle Vene springs (Fig. 4). The calibrated parameters are reported in Table 1 and yield values of E_{rel} and NSE_i equal to 0.83 and 0.80, respectively. Then, validation was carried out on the period from the 5th November 2014 to the 31st May 2016 obtaining values of E_{rel} and NSE_i equal to 0.73 and 0.69, respectively (Fig. 5). In both periods, the simulation of low-flows is satisfactory as values higher than 0.65 are considered good performance levels (Santhi et al., 2001; Moriasi et al., 2007). Moreover, the model correctly reproduced the low-flows and the end of the recession periods (Fig. 4). Instead, as anticipated in the section of the paper describing the model, the higher

Table 1
Calibrated parameters of the modified Hymod model.

C_{max} (mm)	β_k (−)	K_s (d^{-1})
336	0.547	0.015

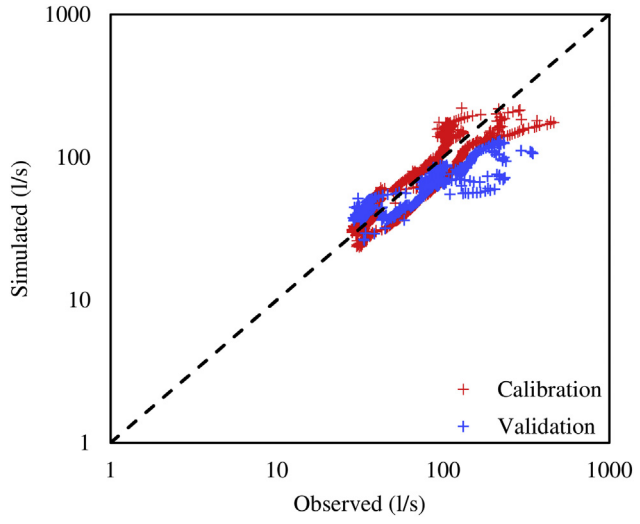

Fig. 5. Simulated and observed daily discharge (in l/s) for the period 2013–2016. Calibration (red cross) and validation (blue cross) periods are also distinguished.

discharge values were not reproduced as the main objective of this work is to analyse the low-flow conditions.

Finally, our modelling exercise enabled us to compute the daily actual evapotranspiration (AET) during the simulation period. The average yearly actual evapotranspiration resulted equal to c.a. 500 mm, with a precipitation about 923 mm, thus the average effective rainfall is c.a. 46% of the total rainfall, which is consistent with the indications reported from other Authors (Scozzafava and Tallini, 2001; Fiorillo et al., 2007; Allocca et al., 2014).

4.2. Baseline and future scenarios

4.2.1. Meteorological data

With respect to the study area, changes between baseline (1984–2013) and future (2021–2050) daily data-series obtained through the downscaling of the five RCMs are statistically significant, as the *P*-values were always lower than 0.05. Results are here reported and discussed as a single ENSEMBLE mean, in order to reduce uncertainties in current climate modelling (Table 2; Table 3, Fig. 6).

No noticeable changes in the mean total annual rainfall have been detected between the baseline period (1984–2013; 810 mm) and the future period (2021–2050; 792 mm) in this area of the Northern Apennines. At the same time, more marked changes can be perceived in the mean monthly rainfall pattern. For the future period (Fig. 6a), the estimates show a general and marked decrease in the amount of monthly rainfall during the summer period (June to September: −78 mm), with an increase of precipitation from January to March (+51 mm). Moreover, the mean annual temperature is seen to increase from 11.5 °C to 12.8 °C, with the main positive changes (Fig. 6e) expected in late spring (+1.3 °C in June), summer (+2.1 °C in July and +1.9 °C in August) and early autumn (+2.0 °C in September and +1.5 °C in October).

The same pattern is repeated for the maximum and minimum temperatures, with an increase for every month (Fig. 6c and d), and becoming more intense in summer and autumn (maximum temperature up to +2.2 °C and +2.1 °C in June and September and minimum temperature up to +2.0 °C in August and September).

The potential evapotranspiration (ETP) assessed with the Hargreaves equation increases from an average of 737 mm in the baseline period to 774 mm in the future (+5%, Fig. 6b). Results are coherent with the typical ranges for ETP values shown in Allen et al. (1998) who indicate a daily evapotranspiration between 1 and 3 mm in temperate humid/semi-arid regions. The standard deviation of the monthly

Table 2
Mean, min and max temperatures (in °C) for observed database (Baseline: 1984–2013) and forecasted Future (2021–2050) scenario together with the corresponding mean annual values. Future values are reported as Ensemble mean of the 5 RCMs with the corresponding standard deviations (±1σ).

Month		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Mean T	Baseline	2.4	3.3	6.4	9.9	14.6	18.6	21.5	21.4	17.1	12.2	6.7	3.3	11.5
	Future	3.8 ± 1.1	4.7 ± 0.2	6.5 ± 0.3	10.3 ± 0.4	15.0 ± 0.4	19.9 ± 0.5	23.6 ± 0.8	23.4 ± 0.7	19.1 ± 0.4	13.6 ± 0.4	8.2 ± 0.5	4.9 ± 0.9	12.8 ± 0.4
Min T	Baseline	−1.1	−0.7	2.3	5.9	10.0	13.7	16.3	16.3	12.4	8.4	3.6	0.2	7.3
	Future	0.8 ± 1.0	1.1 ± 0.1	2.5 ± 0.3	5.8 ± 0.4	10.2 ± 0.4	14.9 ± 0.5	18.2 ± 0.8	18.2 ± 0.8	14.3 ± 0.6	9.7 ± 0.4	4.9 ± 0.7	1.9 ± 1.0	8.5 ± 0.4
Max T	Baseline	5.9	7.3	10.5	14.0	19.3	23.5	26.7	26.6	21.8	15.9	9.9	6.6	15.7
	Future	6.8 ± 1.2	8.4 ± 0.4	10.6 ± 0.4	14.8 ± 0.5	19.7 ± 0.5	24.9 ± 0.6	28.9 ± 0.9	28.6 ± 0.7	23.9 ± 0.5	17.6 ± 0.4	11.5 ± 0.4	8.0 ± 0.8	17.0 ± 0.4

Table 3
Mean monthly precipitation (P) and potential evapotranspiration (ETP) in mm for the observed database (baseline: 1984–2013) and the forecasted future (2021–2050) scenario together with the corresponding mean annual values. Future values are reported as Ensemble mean of the 5 RCMs with the corresponding standard deviations (±1σ).

Month		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
P	Baseline	50	44	73	89	72	68	34	51	73	92	100	64	810
	Future	69 ± 10	69 ± 5	81 ± 5	86 ± 11	75 ± 21	39 ± 10	28 ± 17	25 ± 15	58 ± 23	103 ± 19	88 ± 11	72 ± 12	792 ± 45
ETP	Baseline	22	31	53	67	89	95	106	103	77	49	26	19	737
	Future	21 ± 2	33 ± 2	52 ± 1	72 ± 3	90 ± 3	100 ± 3	112 ± 2	107 ± 2	84 ± 3	53 ± 2	29 ± 1	20 ± 1	774 ± 7

ETP in the future scenarios is very low (few mm). An increase of potential evapotranspiration was assessed for each month, with a maximum of +6 mm in July.

4.2.2. Hydrological model results

As in the case of climate data, the modelling results for the future RCMs have been averaged and are here reported as a single series with corresponding uncertainty (±σ). The average annual actual evapotranspiration decreases from 454 mm in the baseline period to 435 mm in the future period (Table 4). The effective precipitation is almost the same, the 44% in the baseline period and the 45% in the future period. The changes in the monthly behaviour of precipitation and evapotranspiration are interesting. In particular, the actual evapotranspiration AET in the future is estimated to exceed precipitation from June to August, whereas in the baseline period this occurs in July only (Fig. 7). The dryer summer periods can lead to water scarcity or droughts. In fact, the estimated future daily flows from the five RCMs are statistically different from the baseline period, as each *P*-value obtained through Student's *t*-test is less than 0.05.

Despite the mean annual spring discharges remaining almost constant with respect to the baseline (61.8 l/s) and future periods (62.6 l/s), the distribution of the discharge flows within the year changes (Table 4). The monthly spring discharges are expected to decrease slightly (Fig. 8), starting in July (−7.8%), and to reduce continuously until December (−12.9%). The maximum absolute decrease of 10.2 l/s is expected to occur in September and this corresponds to the maximum relative change (−26.3%). Instead, from January to June the future monthly discharges are higher than the baseline ones, ranging from the +25.3% in March to the +3.2% in June.

Fig. 9 shows the FDCs obtained by processing the simulated daily discharges for the baseline (black curve) and future periods (red curve). By looking closely at the FDCs, the largest negative changes involve discharges close to the central part of the curve, with a median flow Q(50) decreasing from 53.3 l/s to 50.6 l/s (−5.1%). On the contrary, high discharges are expected to increase, with Q(05) (i.e., the daily

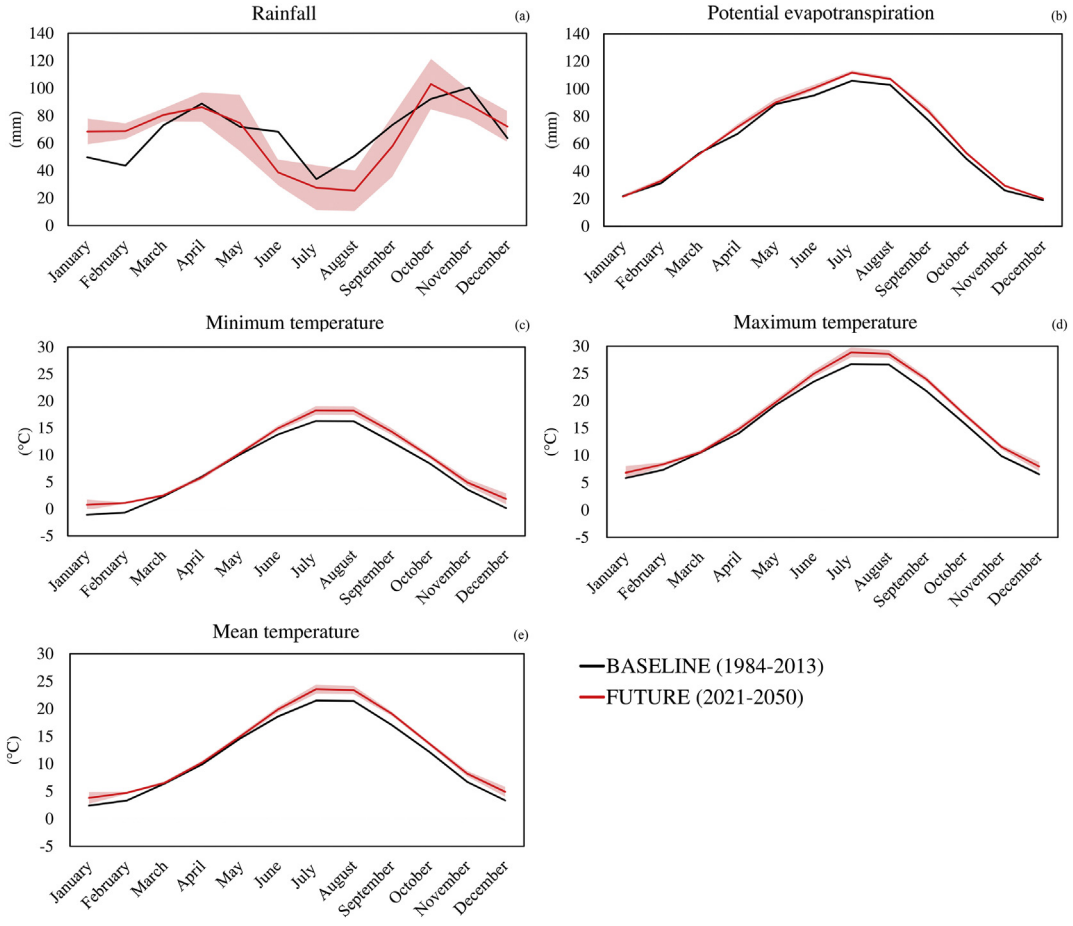

Fig. 6. Comparison between average monthly climate data (a: rainfall; b: potential evapotranspiration; c: minimum temperature; d: maximum temperature; e: mean temperature) for the baseline period (1984–2013; black line) and the future scenario (2021–2050; red line). Uncertainty (as ±σ) of the future scenario is also provided (shaded red area).

Table 4
Mean monthly actual evapotranspiration (AET, in mm) and discharges (Q, in l/s) for the observed database (baseline: 1984–2013) and the forecasted future (2021–2050) scenario together with mean annual values. Future values are reported as mean of the 5 RCMs with the corresponding standard deviations (±1σ). Relative flow changes (in %) are also reported.

Month		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
AET	Baseline	19	26	43	52	64	59	53	43	34	27	19	16	454
	Future	18 ± 1	28 ± 1	44 ± 1	56 ± 1	63 ± 1	59 ± 4	48 ± 5	35 ± 7	27 ± 6	24 ± 3	19 ± 1	15 ± 1	435 ± 21
Q	Baseline	71.6	66.8	69.6	75.3	76.4	68.0	53.4	40.8	38.7	44.9	60.4	76.1	61.8
	Future	74.6 ± 12.4	82.5 ± 6.5	87.3 ± 6.2	87.6 ± 3.8	83.9 ± 9.6	70.2 ± 12.4	49.2 ± 8.9	34.5 ± 6.7	28.5 ± 9.1	35.0 ± 12.8	51.6 ± 14.6	66.3 ± 15.4	62.6 ± 5.1
	Relative changes	+4.3	+23.6	+25.3	+16.3	+9.8	+3.2	−7.8	−15.5	−26.3	−22.0	−14.7	−12.9	+1.2

discharge exceeded 5% of the time during the year) shifting from 133.1 l/s to 154.3 l/s (+15.9%). The Q(95) index decreases from 15.3 l/s (baseline period) to 11.9 (future period; a reduction of -21.8%). At the same time, the 7-day 10-year low-flow index (7Q10) shows a drop from 10.6 l/s (baseline period) to 8.0 l/s (future period; a reduction of −25.0%).

As touched upon in Section 3.3, the duration of continuous low-flows below the threshold Q(80) was assessed for each year for the baseline and the future periods. The results are shown in Fig. 10; it can be observed that, by considering both the baseline and the future periods, the majority of the years are characterized by less than 50 days below the corresponding threshold (17 and 14 years, respectively). It is worth noting the slight increase in the number of years with continuous low-flow lasting between 51 and 100 days (from 6 to 9 years) and between 101 and 150 days (from 2 to 4 years).

5. Discussion

Climate datasets obtained by processing the five RCMs from the A1B scenario for the recharge area of the Mulino delle Vene springs highlighted the fact that there is a simultaneous increase of mean annual temperatures (of about +1.3 °C) and an almost steady mean annual precipitation with respect to the baseline and future periods. These results are in agreement with those found by Tomozeiu et al. (2014) and Dubrovský et al. (2014) for the Northern Apennines in general. In particular, temperatures are expected to increase throughout each month with more intense peaks at the end of summer and beginning of autumn (up to +2.2 °C).

Despite no variation in mean annual flows being found, the estimated changes of the precipitation and actual evapotranspiration pattern can induce changes in the mean monthly future discharges, with more

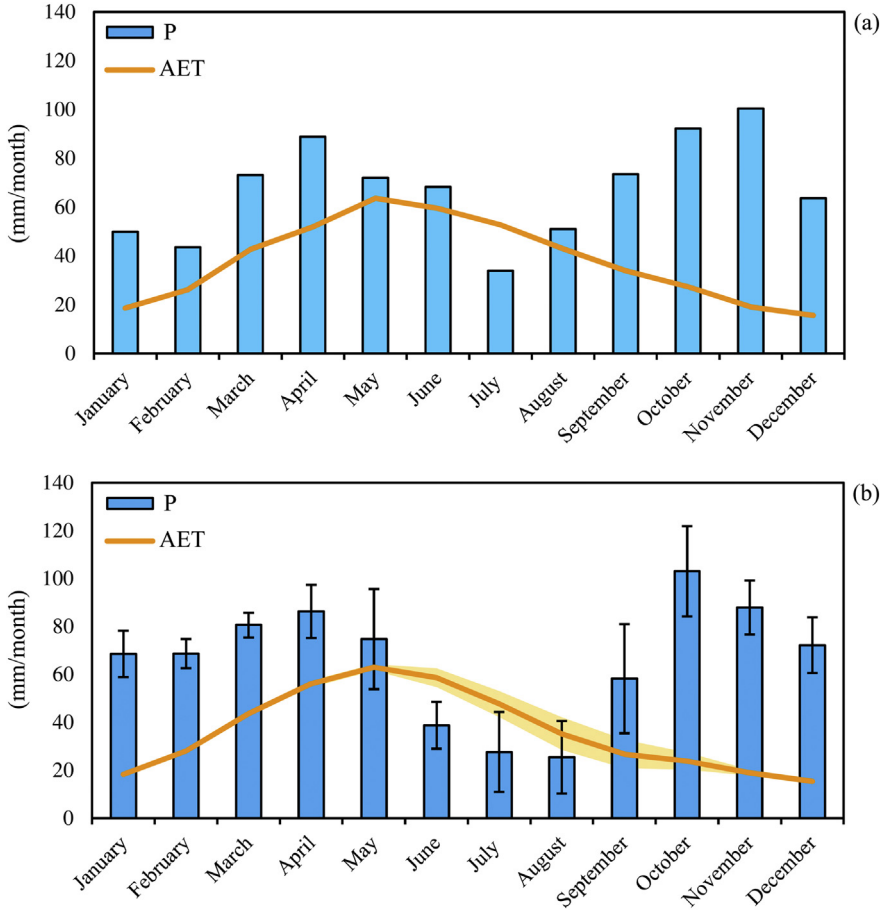

Fig. 7. Average monthly precipitation and actual evapotranspiration in the baseline (1984–2013, a) and future (2021–2050, b) periods along with the uncertainties (as ±σ; black line for precipitation and shaded yellow area for actual evapotranspiration).

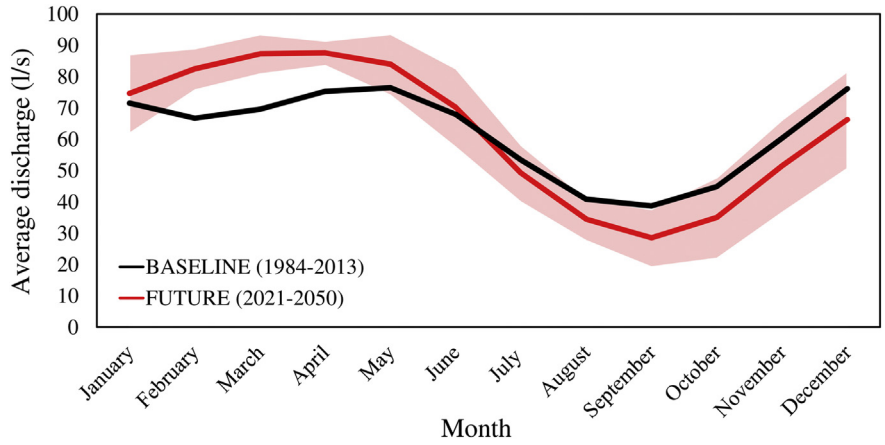

Fig. 8. Average monthly discharges (in l/s) for the actual (1984–2013; black line) and the future (2021–2050; red line) periods along with uncertainty (as ±σ; shaded red area).

marked positive peaks from January to June (maximum of +25.3% in March) and negative peaks from July to December (−26.3% September, −22.0% in October and −14.7% in November, i.e. when the ascending limb of the discharge curve normally begins).

The investigation carried out in this study demonstrates that, in the case of the Mulino delle Vene springs, low-flow length is affected by the future climate scenario, and the number of years when 51 to 100 consecutive days with discharges below the selected threshold Q(80) are expected to increase by a third in the future. Moreover, the number of years with 101 to 150 consecutive days below the Q(80) are expected to duplicate.

With reference to low-flow indices, Q(95) and 7Q10 show a mean decrease of −21.8% and −25.0%, respectively. This means that, although low-flows are caused by the contribution of the less permeable sector of the aquifer and the corresponding low-flow indices obtained from time series of different lengths are somehow reduced (Laaha and Blöschl, 2005), the noticeable decrease in groundwater recharged during the summer and early autumn is so intense that, as a consequence, the low-flow discharges are also reduced.

As can be seen in the FDCs, negative changes also affect the central values, with Q(50) reducing by 5.1%. High flows are clearly increasing (+15.9% of Q(05)), instead, and will occur during winter as a consequence of higher rainfall amounts.

These findings lead to some considerations that can be applied to most springs in the Northern Apennines. Firstly, as the Northern Apennines springs discharging from fractured aquifers are the primary source of water for mountain communities, the future climate data obtained from the five RCMs in the A1B scenario confirm that water management is and will be an issue during the summer-early autumn. The problems associated to water supply during the low-flow period not only will continue in the future, but will get worse, with respect to both the number of years of exceptional drought and to low-flow indices. On the contrary, the increase in the mean monthly discharges expected from January to June will occur in a period when they are

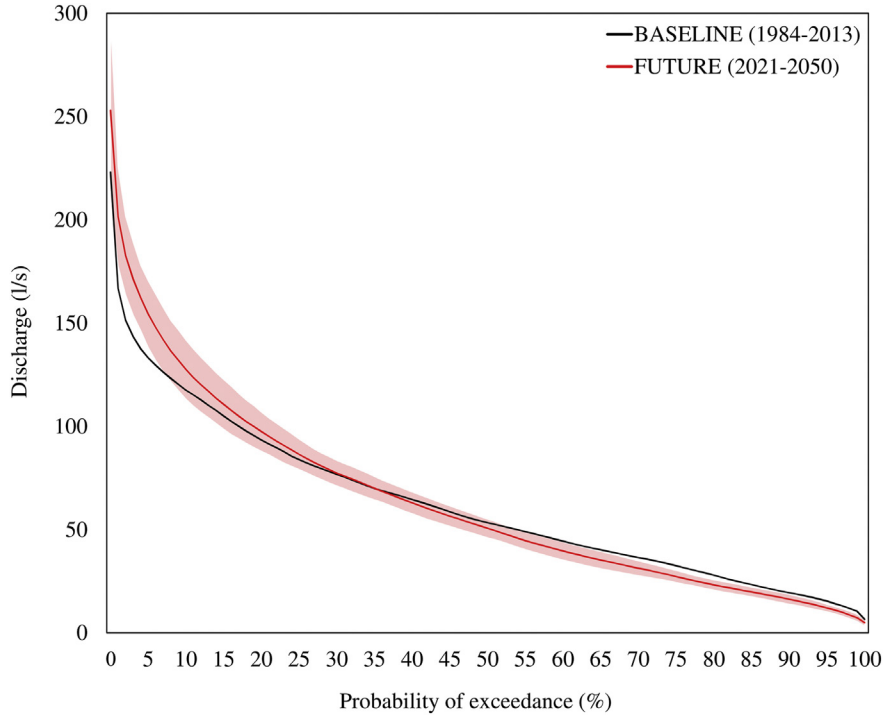

Fig. 9. Flow duration curves for the Mulino delle Vene springs in the baseline (1984–2013; black line) and future (2021–2050; red line) periods.

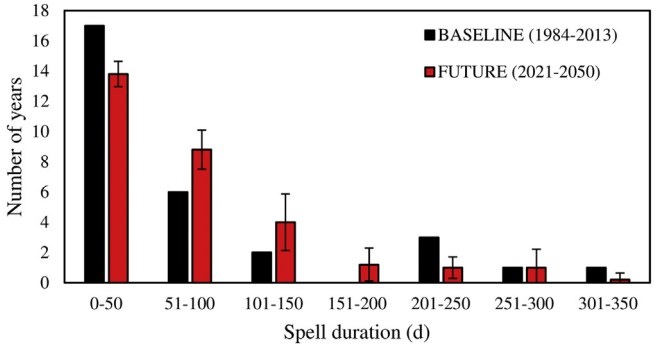

Fig. 10. Histogram of the low-flow duration below the Q(80) thresholds (in d) simulated for the baseline (1984–2013; black bar) and the future (2021–2050: red bar) periods along with uncertainties (as $\pm\sigma$; black line).

already high enough to satisfy the community's water needs, even during the baseline period.

With the aim of reducing the uncertainties in water supply during the most critical months, stakeholders in charge of water management are at present responding by increasing the size of water tanks and constructing artificial reservoirs to collect water from springs and store more water during the night, when less water is consumed. Especially during the low-flow period, this will ensure that the water normally needed during the day is available, i.e. when water consumption exceeds the springs' mean discharge flow.

Another important point consists in the changes that can affect the interaction between groundwater and surface water, both in terms of their qualitative and quantitative status (Werner, 2012; Skoulikidis et al., 2016). With reference to climate change, this topic has already been discussed in mountain areas worldwide (Scibek et al., 2007; Goderniaux et al., 2009; Voeckler et al., 2014). In the specific case of the Mulino delle Vene springs, because they are the main groundwater source of the river Tresinaro, the estimated intra-annual changes for the future period (2021–2050) could slightly modify the river flow downstream from their confluence. Furthermore, it should be emphasized that rivers flowing from the Northern Apennines supply the porous aquifers of the alluvial plain of the river Po (Regione Emilia-Romagna, ENI-Agip, 1998; Farina et al., 2014). Here, dozens of wells draw groundwater for civil and industrial purposes to satisfy the needs of hundreds of thousands of people (Martinelli et al., 2014). Recently, Di Dio (2012) demonstrated that the recharge process of these aquifers is complex and, due to the interdependency between river water level and groundwater, recharge mainly takes place during the low-flow season. This means that, during that period, the simultaneous reduction of groundwater quotas released by mountain aquifers (mainly composed of fractured sedimentary rock units) to the river network, coupled with the estimated changes in the mean monthly effective rainfall over the whole catchment area, could result in changes to the recharge process of these porous aquifers. This is a significant issue because these aquifers are already displaying clear signs of water shortage, as a consequence of a severe over-exploitation (Farina et al., 2014).

6. Conclusions

Our study presents an adaptation of a widely-known hydrological model (i.e. HyMOD, see e.g. Boyle, 2001) to model the hydrological regime of Mulino delle Vene springs, a typical example of freshwater springs of the Italian Northern Apennines. The model was calibrated and validated based on meteorological and hydrometric data collected since 2013, leading to a very satisfactory performance in simulating the low-flow regime of the study springs (e.g. relative efficiency E_{rel} resulted equal to 0.83 in calibration and to 0.73 in validation).

The model implementation is then used to perform a quantitative analysis of possible climate change impacts on the springs system, based upon data from the five RCMs obtained through the ENSEMBLE project and its A1B SRES IPCC emission scenario. In particular, the hydrological model was constructed to simulate the baseline (1984–2013) and future (2021–2050) daily discharges. Although a remarkable uncertainty affected the rainfall forecasts, some robust trends with regard to the discharge pattern were detected. In detail, results show no change in springs' mean annual discharge, but a significant alteration in the intra-annual discharge pattern. In fact, due to the increase in recharge amounts at the beginning of the year, the springs' discharges are expected to increase slightly from January to June (up to +25.3%).

On a different note, the estimated reduction of effective rainfall from June to November will likely lead to a significant decrease in future discharges over the same period (up to −26.3%). The climate scenario implies decreases to both the central values Q(50) (−5.1%) and low-flow indices such as Q(95) (−21.8%) and 7Q10 (−25.0%). Low-flow lengths are also affected, with more years in the future presenting exceptionally long continuous low-flows, below the corresponding thresholds Q(80) (in particular, years with continuous low-flows of between 51 and 100 days).

These findings can lead to broader considerations if one refers to the entire system of Italian Northern Apennines. Here, since most of the springs are fed by low-yield fractured aquifers, the impact could be similar to that found for the Mulino delle Vene springs, under climate scenarios that bring about changes to the recharge distribution pattern during the year. Furthermore, changes in groundwater intra-annual discharges, together with the changes to rainfall pattern in the catchment areas, can also influence the river network in terms of its hydrological and ecological behaviour and potentially alter the process of recharging the porous aquifers in the alluvial plains.

Since the question concerning the impact of climate change on groundwater resources in the Italian Northern Apennines has never been addressed in the literature, we believe that these results may have important implications, crucial for the water supply in this area, with special reference to the adaptation measures to be pursued by stakeholders to reduce the threat of drought.

Further efforts will be directed towards the quantification of the interactions between groundwater and surface water in mountain areas in Northern Apennines and the possible impact of the future climate change on the recharge of alluvial aquifers in the Po plain. To date, studies have focused on the Tresinaro river area, where a system was recently set up for the continuous monitoring of the piezometric levels and discharges in several sectors of the catchment area. Using these data, future analyses could for instance build and validate a physically based, spatially distributed and integrated hydrogeological model of the Tresinaro catchment. The application of an integrated model allows a simultaneous solution of both the surface and variably-saturated subsurface flow equations, enabling one to better simulate the groundwater-surface water interaction processes. Moreover, the model could be used in combination with climate change scenarios to assess the potential impacts on the catchment hydrological cycle and water resource.

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